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AUTHOR: T. T. Fu, Ph D

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NOTE

NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

°F -40   0   32   40   80   98.6   120   160   200   212
°C -40 -20   0   20   37   40   60   80   100

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.
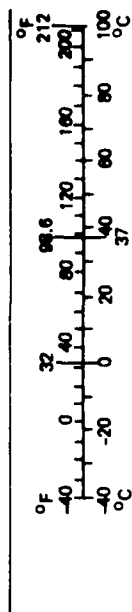
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Extensive tests have been conducted in an in-service boiler to determine the measurable benefits of firing water in no. 6 oil emulsions. Emulsions of 3%, 6%, 9%, and 12% water concentrations have been fired during normal boiler operations. Although the emulsions could be fired satisfactorily without modifications to boiler equipment, the test results show that improvements, if any, in overall boiler efficiency or emissions were ambiguous.

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Extensive tests have been conducted in an in-service boiler to determine the measurable benefits of firing water in no. 6 oil emulsions. Emulsions of 3%, 6%, 9%, and 12% water concentrations have been fired during normal boiler operations. Although the emulsions could be fired satisfactorily without modifications to boiler equipment, the test results show that improvements, if any, in overall boiler efficiency or emissions were ambiguous.

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INTRODUCTION

The use of water-in-oil emulsion as a fuel has been offered as an
effective means for promoting clean combustion, reducing maintenance
requirements, and improving boiler efficiency. Many studies made during
the last decade have produced varied results, but the true merit of
emulsion burning has not been determined. From an energy conservation
standpoint, the potential for reduction in operation and maintenance
costs is worth a detailed evaluation for Navy stationary boilers.

At the recommendation of the Naval Facilities Engineering Command,
the Naval Civil Engineering Laboratory (NCEL) procured an emulsion
system to determine the benefits of emulsion burning and its potential
for Navy applications. Since water can be dispersed in heavy fuel oil
much more stably than in light fuel oil, emulsions of water in no. 6
fuel oil (heavy fuel oil) were considered for this evaluation.

Because of funding constraints and the delivery time of the hardware,
the overall effort was carried out in two steps:

1. FY81 -- System installed in a suitable boiler plant, and
   preliminary tests conducted

2. FY82 -- Detailed performance evaluations made

This report is a summary of the results.

BACKGROUND

Oil is a conventional boiler fuel. Because of cost advantages,
heavy fuel oil, also called residual oil, is commonly used in relatively
large boilers. However, the burning of heavy fuel oil rather than light

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fuel oil is more involved because of the requirements for fuel handling, environmental control, and routine maintenance.

Depending on the origin of the crude, heavy fuel oil can contain varied amounts of chemical compounds that will form combustion products harmful to the boiler or the environment or both. Therefore, research in fuel oil combustion has concentrated on methods for improving boiler efficiency without sacrificing environmental quality. These efforts can be classified into two broad categories: fuel additives and combustion modification. With the former, chemicals are introduced into low quality fuels (e.g., fuels containing high concentration of vanadium, sludge, or other materials) so they can be burned in an environmentally acceptable manner. Combustion modification uses mechanical means to achieve low emissions.

For complete combustion, fuel oil must be properly atomized and well mixed with the surrounding air. In practice, excess air must be supplied to ensure complete combustion. A significant energy loss occurs when the hot combustion products (the flue gas) are exhausted through the stack. In order to maintain a boiler at high operating efficiency, excess air must be held to a minimum.

Benefits of Water-in-Oil Emulsions

Some water is always present in fuel oils. Since the water in oil does not pollute upon combustion, it may be regarded as an attractive additive. Deliberately introducing water in oil has aroused the interest of many, because it is conjectured that by suspending water in oil to form an emulsion, clean and complete combustion could be achieved. Thus, boiler efficiency could be improved.

The benefits of emulsion burning are claimed to be derived from the phenomenon "microexplosion." A drop of water-in-oil emulsion is physically a drop of oil with small water particles suspended in it. During combustion, these water particles receive heat from their surroundings and eventually become superheated. A sudden increase in volume occurs due to vaporization of the water particles. This "explosion" causes a drop

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of oil to shatter into smaller pieces that result in (1) a secondary atomization, and (2) more intimate contact between oil and its surrounding air. These are the fundamental requirements for complete combustion. Thus, the potential benefits of emulsion burning are:

1. Reduced direct energy loss through the stack due to a lower air requirement

2. Improved heat transfer due to cleaner boiler heat transfer surfaces

In actual practice, some users have reported 3% to 4% increase in overall boiler efficiency. However, others have reported little or no beneficial effects, but cleaner combustion and boiler fire-side surfaces appear to be reported by all.

Producing A Water-in-Oil-Emulsion

Water-in-oil emulsions can be produced by several methods with or without the addition of surfactants as stability improvers. The methods consist of:

1. Venturi -- introducing water into the oil stream at the throat of a venturi

2. Static mixing -- passing the proportioned mixture of water and oil through a "static mixer"

3. Ultrasonic agitation -- introducing ultrasonic energy into the mixture

4. Homogenizing -- mechanically blending the mixture at high pressure and speed

5. Cavitation -- introducing water into the cavitation region created by the oil flow

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The cavitation emulsification method was chosen for NCEL's test work after the following items were considered: energy requirements, emulsion quality (e.g., uniformity, stability, water particle sizes and distribution, requirement for stability improving additive), continuous production rate, cost, experience reported in the literature, and, most importantly, availability.

TEST FACILITIES

Emulsification System

A commercial emulsification system that uses the cavitation principle was procured. This system is designed to prepare water and no. 6 fuel oil emulsions for in-line installations. The basic components of the as-delivered system are motor, pump, oil flowmeter, water flowmeter, emulsion chamber, series of solenoid valves to control the water flow, and control box. Some modifications were made: two flow meters, and four needle valves for vernier control of the waterflow were added, and an alternate location for introducing water to the system (i.e., bypassing the "emulsion chamber") was installed. The overall arrangement of this modified system is shown schematically in Figure 1. As can be seen, this system can be readily connected to the fuel lines so that the burner can be operated either with or without emulsion by simple valve manipulation. The actual installation of the system is shown in Figure 2.

During operation, the oil flowmeter sends a signal to the control box which, depending on the flow rate, activates one or more of the solenoid valves to admit water into the emulsion chamber. Solenoid valve actuation is controlled by four independently adjustable potentiometers which apply a reference voltage to an electronic comparator. When the output voltage of the flowmeter exceeds the reference voltage selected for each valve, a relay is actuated to energize that solenoid valve. For example, for oil flows between 1 and 2 gpm, no. 1 solenoid valve opens; for 2 to 3 gpm, no. 1 and no. 2 solenoid valves open; and so forth. In an emergency (such as when the burner is turned off by a

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safety device), oil flow through the flowmeter will cease, and all the solenoid valves will close, thus providing a fail safe operation. An overpressure sensing switch is provided to interrupt power to the oil pump in case the pump discharge pressure rises above a preset safe limit. The system can be easily turned on or off by pushbutton switches at the control box.

Boilers

An important requirement for the test boiler was that it be capable of firing heavy fuel oils. The boilers at the Naval Weapons Center (NWC), China Lake, Calif., were chosen for this purpose because they were the most accessible to NCEL. The No. 4 boiler in Plant No. 1 was used for the preliminary tests, while the No. 8 boiler in Plant No. 3 was used for all the detailed performance evaluation work.

These boilers are primarily used for utility heating and normally carry a higher load during the day time of week days. The actual boiler loads varied, depending on the outside air temperature, but they always carried a minimum load of approximately one-third the rated capacity during the test periods.

Boiler No. 4. This is a water-tube, single-burner boiler that can be fired either on no. 6 fuel oil or on natural gas. A steam atomization nozzle is used for firing oil. This boiler produces 125-psi saturated steam and has a rated capacity of 20,700 lb/hr. It was previously used by NCEL for demonstrating waste oil burning (Ref 1) and was chosen because of its adaptability for experimental work. A partial view of this boiler and the piping for the emulsion system leading to the burner is shown in Figure 3a.

Boiler No. 8. This is also a water-tube, single-burner boiler, but it is fired only on no. 6 fuel oil. Again, a steam atomization nozzle is used. The boiler produces 100-psi saturated steam and has a rated capacity of 20,000 lb/hr. It was chosen for all the detailed performance evaluations because it could only be fired on no. 6 fuel oil, thus

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eliminating any concern for cost differentials for fuels.* The front face of this boiler and the emulsion system as installed are shown in Figure 3b.

Instrumentation

In addition to the standard instrumentation for these boilers, an automatic stack gas analysis system was installed to continuously monitor the stack gas emissions. The essential components of this system are a heated sample line, a sample conditioning system to quickly remove moisture in the sample gas (drying by refrigeration), a stack gas temperature probe, a logic system to control the overall operation and automatically actuate the appropriate calibration gas valves for calibrating the gas analyzers (oxygen, carbon monoxide, nitrogen oxides) at preselected time intervals, calibration gases, and a four-channel strip chart recorder to record the stack gas temperature and outputs from the gas analyzers. A schematic of this system is shown in Figure 4, while the front and interior views are shown in Figure 5.

PERFORMANCE CALCULATIONS

The performance evaluations were based on energy conservation and environmental impact because these are the most important considerations in any combustion system performance. Therefore, the overall boiler efficiencies and the pollutant emissions at these efficiencies when burning no. 6 fuel oil alone or when burning emulsions at several water concentrations were measured and compared. The maintenance requirements and long-term effects on boiler components were then determined only if significant advantages of burning the emulsions could be demonstrated from test results. This report describes only the subjects relevant to the determination of boiler efficiency and pollutant emissions.

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*Natural gas is cheaper than fuel oils.

Fuel

The fuel for the tests was a low sulfur, no. 6 fuel oil that con-
formed to the local air pollution control regulations which specify
<0.5%. It was drawn from a 25,000-gallon underground tank. This large
a tank required fuel delivery from several tank cars. Since some varia-
tions in fuel properties always existed among the deliveries, only the
average typical properties are meaningful.

The fuels delivered during the test period had an average gravity
of 20.4 degrees API at 60°F which corresponds to a specific gravity of
0.9315 and a density of 7.757 lb/gal at 60°F. Based on this average
gravity and the data given in Reference 2, the following composition is
estimated and used for all the calculations described in this report:

Components	Weight (%)
Carbon	86.54
Hydrogen	11.14
Sulfur	0.47[a]
Nitrogen	0.20
Oxygen	0.50
Ash	0.05
Moisture	1.10
Total	100.00

[a]NWC analysis

In addition, a high heating value was estimated as 18,752 Btu/lb. From
Reference 3, the coefficient of thermal expansion of an oil in the
temperature and gravity ranges of interest is 0.000385/°F. The density ρ
of this oil at temperatures T other than 60°F can, therefore, be calculated
from the density at 60°F (ρ_{60}) as follows:

$$\rho = \frac{\rho_{60}}{1 + 0.000385(T - 60)} \frac{lb}{gal} \qquad (1)$$

Combustion Calculations

The combustion of a petroleum fuel such as that used for the tests in air will produce CO, CO_2, SO_2, H_2O, etc. When all the carbon, hydrogen, and sulfur in the fuel are converted respectively to CO_2, H_2O, and SO_2, the combustion process is defined as complete. The amount of air theoretically required for completing the combustion is called stoichiometric air. In order to promote complete combustion, more air than is theoretically required is always supplied for all combustion processes. This additional air is called the excess air and is expressed in terms of a percentage of the stoichiometric air (for example, 15% excess air).

The stoichiometric air requirement for a fuel of known composition can be readily calculated, and the amount of excess air for an actual combustion process is usually determined from the oxygen content in the combustion products. Some basic calculations are discussed here. Consider the following reactions:

$$C \quad + \quad O_2 \quad \rightarrow \quad CO_2$$
$$1 \text{ mole} + 1 \text{ mole} \rightarrow 1 \text{ mole}$$
$$12 \text{ lb} + 32 \text{ lb} = 44 \text{ lb}$$

$$2H_2 \quad + \quad O_2 \quad \rightarrow \quad 2H_2O$$
$$2 \text{ moles} + 1 \text{ mole} \rightarrow 2 \text{ moles}$$
$$4 \text{ lb} + 32 \text{ lb} = 36 \text{ lb}$$

$$S \quad + \quad O_2 \quad \rightarrow \quad SO_2$$
$$1 \text{ mole} + 1 \text{ mole} \rightarrow 1 \text{ mole}$$
$$32 \text{ lb} + 32 \text{ lb} = 64 \text{ lb}$$
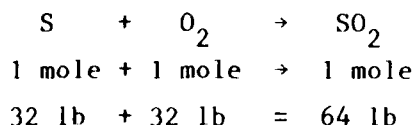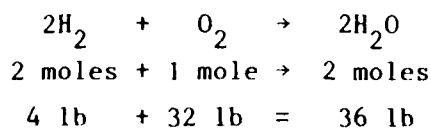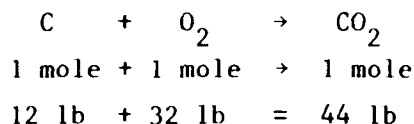
Since equal volumes of gases at any given pressure and temperature contain the same number of molecules (Avogadro's law), the weights of equal volumes of gases are, therefore, proportional to their molecular weights. In the above reactions, the second lines represent the volume relationships, and the third lines represent the weight relationships. (Note that there is a balance in the weight but not in the volume.)

Thus, 8/3 pounds of oxygen is theoretically required to burn completely 1 pound of carbon; 8 pounds of oxygen is required to burn 1 pound of hydrogen; and 1 pound of oxygen is required to burn 1 pound of sulfur.

Based on the above, let C, H, O, N, and S represent the weight fraction of the chemical elements in a fuel. The oxygen theoretically required to completely burn this fuel (stoichiometric oxygen) will be

$$\frac{8}{3} C + 8 \left(H - \frac{O}{8} \right) + S, \text{ lb oxygen/lb as-fired fuel}$$

Since the weight ratio of nitrogen and oxygen in air is

$$\frac{0.7685}{0.2315} = 3.32$$

the stoichiometric air requirement will be

$$4.32 \left[\frac{8}{3} C + 8 \left(H - \frac{O}{8} \right) + S \right]^{*}, \text{ lb/lb as-fired fuel}$$

Let

       X_a = excess air, weight fraction of stoichiometric air

  O_2, CO_2 = volume or mole fraction of O_2, CO_2 in dry combustion products

       A = (8/3)C + 8[H − (O/8)] + S = the theoretical oxygen requirement, constant for a given fuel

       B = 0.7685/0.2315, the weight ratio of nitrogen and oxygen in air

Since the volume of a gas in number of moles is equal to the weight divided by its molecular weight,

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*The nitrogen in the fuel is very small compared to that in the combustion air and is therefore neglected.

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$$X_a \cdot A/32 = \text{moles of oxygen}$$

$$C/12 = \text{moles of carbon dioxide}$$

$$H/2 = \text{moles of water vapor}$$

$$(1 + X_a) \cdot A \cdot B/28 = \text{moles of nitrogen in the combustion air}$$

From these expressions, the following can be derived for dry combustion products (water vapor is not considered):

$$O_2 = \frac{21 \, A \cdot X_a}{21 \, A \cdot X_a + 56 \, C + 24(1 + X_a) \cdot A \cdot B} \qquad \text{(volume fraction of oxygen in dry combustion products)}$$

$$X_a = \frac{(56 \, C + 24 \, A \cdot B) \cdot O_2}{21 \, A - (21 \, A + 24 \, A \cdot B) \cdot O_2} \tag{2}$$

$$CO_2 = \frac{7 \, C - (7 + 8 \, B) \, C \cdot O_2}{7 \, C + 3 \, A \cdot B} \tag{3}$$

Equations 2 and 3 are helpful in monitoring boiler operating conditions. Using the average fuel composition presented earlier in the text table, one obtains A = 3.199 and B = 3.320. Equations 2 and 3 reduce to

$$X_a = \frac{4.515 \, O_2}{1 - 4.794 \, O_2} \tag{2'}$$

$$CO_2 = 0.160 - 0.767 \, O_2 \tag{3'}$$

These equations are plotted as curves A in Figure 6. Curves B in this figure are for a fuel of slightly different composition. A comparison of curves A and B shows that O_2 is fairly insensitive to small variations of fuel compositions. Therefore, in addition to being a reliable indicator of the presence of excess air, O_2 is more desirable for monitoring boiler operations than CO_2, which can be used to verify the consistency of O_2 measurements.

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Boiler Efficiency Calculations

The following two methods were used for determining boiler efficiency:

Output/Input Method. Since a boiler is intended for producing
steam, its efficiency may be measured by its effectiveness in producing
usable steam to be exported; i.e., the ratio of the energies in the
steam exported and the corresponding fuel consumed. Figure 7 shows
notations for the boiler efficiency calculations involved.

Based on experience, the quality x of the exported steam closely
equals 0.98. At the measured steam pressure p, the steam enthalpy h_s
can be calculated as follows:

$$h_s = (1 - x) h_f + x \cdot h_g \qquad (4)$$

where h_f and h_g are, respectively, the enthalpies of saturated liquid
water and steam at pressure p. Since the fuel is used to heat the
feedwater and convert it to steam, the energy output is*

$$Q_{out} = W_s (h_s - h_w) \qquad (5)$$

where W_s = total exported steam during some time interval, lb

$h_w = h_w (p,T)$, feedwater enthalpy

W_s was measured with a conventional orifice type flowmeter and integrator
at the boiler plant.

The energy input to the boiler consists of the sensible heat in the
water and oil and the heat of reaction from burning the oil -- the high
heat value HV. Let W_o and C_{po} be, respectively, the total amount of oil

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*Due to the large thermal inertia of a boiler, instantaneous values,
especially for energy measurements, are often misleading. Only quanti-
ties measured for a sufficiently long period of time are considered
meaningful and are therefore used throughout this discussion.

consumed during some time interval, and the constant pressure specific heat of the oil; also let W_w and C_{pw} be those for the water in the emulsion. The total energy input to the boiler will be

$$Q_{in} = W_o \cdot HV + (W_o C_{po} + W_w C_{pw})(T_e - T_r) \qquad (6)$$

where T_e is the temperature of the emulsion, and T_r is the reference temperature for computing the heating value. The oil flow was measured with a turbine rate meter and a positive displacement cumulative meter. The water flow was measured with a rotameter and a positive displacement cumulative meter. During the tests, the flowrate meters were used to obtain the desired conditions, but only the total flows from the positive displacement meters were used for efficiency calculations.

From above, the average boiler efficiency η over a suitably chosen period of time can be calculated as

$$\eta = \frac{Q_{out}}{Q_{in}} = \frac{W_s(h_s - h_w)}{W_o \cdot HV + (W_o C_{po} + W_w C_{pw})(T_e - T_r)} \qquad (7)$$

and the water concentration c of the emulsion as

$$c = \frac{W_w}{W_o + W_w} \qquad (8)$$

Heat Loss Method. This method is basically different from the Output/Input Method and, therefore, can be used to verify the consistency of the test data and the calculated results. Heat is lost from the boiler primarily through the hot stack (or flue) gas exit and, to a lesser extent, through radiation and convection from boiler exterior surfaces, through heat contained in the blowdown waters, and through the miscellaneous steam-operated boiler accessories. Useful energy is, therefore, the difference between the energy released by fuel (Q_{in} described earlier) and the losses. The average boiler efficiency is, therefore

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$$\eta = \frac{Q_{in} - losses}{Q_{in}} = 1 - \frac{losses}{Q_{in}} \qquad (9)$$

Among all the heat losses, only the stack loss is highly variable. Its variability depends on the amount of excess air and the stack gas temperature which is affected by the boiler load and the cleanliness of the boiler gas-side heat transfer surfaces. For a given boiler operating at a more or less constant steam pressure and, hence, at a constant temperature, the radiation and convection losses through the fixed boiler exterior surfaces are practically a constant. At steady operating conditions, the losses due to blowdowns and operation of auxiliary equipment are also practically a constant. Consequently, only the losses through the stack require detailed discussions.

Heat loss through the stack can be considered in two parts: loss carried away by dry stack gas, and loss by water vapor.

(a) Loss Due to Dry Stack Gas. From Reference 4, the weight of dry stack gas is approximately

$$W_g = \frac{44\ CO_2 + 32\ O_2 + 28\ N_2 + 28\ CO}{12(CO_2 + CO)} \left(C + \frac{12}{32} S \right)$$

The CO measured during all the tests was very small (<100 ppm) and, therefore, can be neglected from the above expression. Since

$$N_2 = 1 - CO_2 - O_2$$

the above expression is simplified to

$$W_g = \left(C + \frac{3}{8} S \right) \left(\frac{7 + O_2 + 4\ CO_2}{3\ CO_2} \right), \text{ lb/lb of as-fired fuel} \qquad (10)$$

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and the loss due to dry flue gas in % of as-fired fuel,

$$L_g = W_g \, C_{pg}(T_g - T_a)/HV \tag{11}$$

where C_{pg} = mean specific heat of dry stack gas (Figure 7 of Ref 4)

T_g = stack gas temperature

T_a = inlet air temperature

Note that W_g can be calculated from Equation 10 using either both the O_2 and the CO_2 measurements or only the O_2 measurement in conjunction with Equation 3.

(b) Loss Due to Water Vapor. The water vapor in stack gas (in lb/lb of as-fired fuel) comes from:

Combustion of hydrogen in the fuel	= 9 H
Moisture in the as-fired fuel	= FM
Moisture in the combustion air	= $(1 + X_a) \, A \cdot \phi / 0.2315$
	$\approx 0.18 \, (1 + X_a)$
Water for making the emulsion	= FEW

where $\phi \approx 0.013$ lb/lb of dry air, specific humidity of air, and

A = 3.199 lb of stoichiometric oxygen per lb of as-fired fuel for the fuel used in the tests

Let

h_1 = enthalpy of water vapor at the stack gas temperature T_g

h_2 = enthalpy of liquid water at the fuel temperature T_f

C_{pa} = mean specific heat of water vapor in air ≈ 0.47 Btu/lb

The loss due to water (in % of as-fired fuel) will be:

$$L_w = \frac{(h_1 - h_2)}{HV} \left(9 \ H + FM + \frac{FEW}{1 - FEW} \right) + \frac{0.18 \ C_{pa} (1 + X_a)}{HV} \tag{12}$$

c. <u>Loss Due to Radiation and Convection</u>. As discussed earlier, this loss is more or less a constant. It can be estimated using the standard radiation loss chart of American Boiler Manufacturers Association or can be found in Reference 4.

Assuming 1% unaccounted-for losses, the efficiency of the boiler by the heat loss method may be computed from Equation 9 using Equations 11, 12 and standard radiation loss chart (Ref 4).

TEST DESCRIPTION

As discussed earlier, boiler efficiency is a function of the excess air or the oxygen concentration in the stack gas. Since the oxygen concentration at a given firing rate can be set more or less at any level (not a unique quantity), additional constraints have to be imposed. For this, the smoke level and CO concentration were chosen as the limiting constraints; that is, the burner air was adjusted so that the oxygen concentration was at the lowest possible level without it producing environmentally unacceptable smoke or CO levels. Bacharach smoke spot number 6 and CO concentration of 100 ppm were used as the upper limits.

During tests at a given stabilized steam load, the burner air was adjusted to the minimum level while either the Bacharach smoke spot number was 6 or less or the CO concentration was 100 or less or both. This adjustment was done in two steps:

1. The fuel valve opening was adjusted so that the correct amount of <u>oil</u> was delivered to the burner in order to maintain the steam pressure and to meet the steam demand.

2.   The stack damper was adjusted so that minimum oxygen concen-
     tration in the stack gas consistent with the smoke and CO
     constraints was achieved.

Step 1 was necessary because the fuel valve is a volumetric control
device. Therefore, when an emulsion passes through the valve, for the
same volumetric flow, the actual amount of oil delivered to the burner
nozzle is decreased by the amount of water in it. Insufficient oil
means insufficient heat input which causes steam pressure to drop and
the boiler to be unable to meet the steam demand. Therefore, when
emulsion is fired, the fuel valve must be opened to an appropriate
amount to compensate for this effect. Since the water in an emulsion
(or, fuel) actually displaces the oil, increasing the water while holding
all boiler settings unchanged would result in an increase in excess air
for the combusion process. This effect is readily seen by the apparent
increase in oxygen concentration in the stack gas as shown in Figure 8
(see also analysis in Appendix A). This excess air increase means the
combustion is cleaner, which often leads an observer to believe that
emulsion burning is more efficient.

The parts of the boiler where these adjustments were made are shown
in Figure 9. The adjustments, which took about 30 minutes, were based
on the stack gas oxygen concentration readings.

The water concentration in the emulsion was set by using the four
needle valves upstream of the location where the water is injected into
the emulsion chamber; this adjustment was based on the readings of a
rotameter for water flow and a turbine flowmeter for oil flow. Since
these flow rate meters have relatively fast responses, they rarely give
stable readings; but they were satisfactory for setting and monitoring
the water concentrations in the emulsion. Due to the large thermal
inertia and intermittent operations of boiler controls and steam-using
devices (being the inherent nature of boilers), only time-averaged
quantities are meaningful. Therefore, the actual flow rates of water
and oil were obtained from positive displacement flow integrators for a
sufficiently long period of time (10 to 15 minutes).

Following the procedure outlined, time-averaged data were obtained for several boiler steam loads. At each boiler load, the burner was first fired on no. 6 fuel oil (no water) to establish a set of baseline data and then on emulsions at four water concentrations (3%, 6%, 9%, and 12%). Data recording for each condition began after the adjustments were made and stable running conditions were achieved. The entire set of data was taken every 10 or 15 minutes for several times to minimize human errors and provide a sound basis for averaging.

TEST RESULTS

In the early part of the tests, Boiler No. 4 was used. These tests were of a preliminary nature and were intended primarily for demonstrating the operational aspects of the emulsification system in an in-service boiler. No elaborate adjustments were made, and the boiler was operated at water concentrations between 0 and 15% in the same manner as burning no. 6 oil. Approximately 6,000 gallons of no. 6 oil were consumed during these tests. No difficulties of any kind were encountered. No operational difference was experienced between burning no. 6 oil and emulsions.

All the detailed evaluation work was done using Boiler No. 8. The results presented below are for the boiler operating at minimal oxygen (or, minimal excess air) subject to the constraints of not exceeding Bacharach smoke spot no. 6 or CO concentration of 100 ppm in the stack gas. This was successfully achieved by the adjustments. Due to a mild winter and measures taken to conserve energy, the possible steam loads varied only between 5,400 and 9,200 lb/hr during the entire test period.

Emulsions

Four water concentrations were used for each of the several steam loads tested. Samples of these emulsions were taken during each test and visually examined under a microscope to determine their qualitative features. It was found that the water particles were smaller than 10 μm

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in diameter and were uniformly dispersed in the oil. A comparison of these emulsions is shown in Figure 10. As expected, dense water particle distribution is associated with high water concentration.

Since no. 6 fuel oil is a very viscous fluid, and its density is fairly close to that of water, the emulsions were expected to be stable. One emulsion sample was examined under a microscope at the time of the tests and then four months later; no appreciable differences were discernible. Judging from this, the storage life of these emulsions at room temperature is very likely to be indefinite.

Also of great interest was determination of the role and contribution of the emulsion chamber in the overall emulsification system. To this end, an alternate location downstream of the emulsion chamber was chosen to inject water into the system (see Figure 1). The emulsion produced in this manner was not visibly different from that produced through the emulsion chamber in both microscopic features and boiler firing. This result is believed to be primarily due to the high shear rate taking place in the pump and the high recirculation rate of the mixture in the system. Based on the pump capacity and the firing rate, about 90% of the mixture is recirculated. Therefore, the contribution of the emulsion chamber would be unimportant.

Emissions

The emissions from an oil-fired boiler consist primarily of sulfur oxides, unburned hydrocarbons, carbon monoxide, nitrogen oxides, and smoke. Since oil is regulated through its sulfur content and unburned hydrocarbons are the result of incomplete combustion that can be indicated by the presence of carbon monoxide, only carbon monoxide, smoke, and nitrogen oxides were monitored.

Figures 11 and 12 summarize, respectively, the average Bacharach smoke spot number and the carbon monoxide concentration measured during all the tests, plotted against water concentration in the fuel. Since these measurements are actually the limiting constraints used for adjusting the boiler, they also describe the operating envelope for all the tests conducted. In Figures 11 and 12, the points on the vertical axis are

the baseline data, that is, for no. 6 oil burning. All other points are
for emulsion burning. The merits of emulsion burning relative to burning
only no. 6 oil, therefore, may be seen from these data. Other than the
relatively large departure* from the main group of data points at the
high boiler loads, there appears to be a slight trend toward decreasing
smoke and carbon monoxide emissions as the water concentration increases.
Emulsion burning appears to result in lower emission levels.

The emission of nitrogen oxides for the same operating conditions
is shown in Figure 13; the same qualitative features as described earlier
are found. The oxygen concentration in the stack gas for all the test
conditions was adjusted (fuel valve and stack damper) to between 0.8%
and 1.5% according to the procedure described in the TEST DESCRIPTION
section. Figure 14 is a set of data illustrating the achievable oxygen
(or excess air) reduction through these adjustments. The smoke and
carbon monoxide levels are slightly increased at low oxygen, but the
boiler efficiencies are increased by about 2 percentage points, a very
significant improvement. Figure 15 is a summary plot that illustrates
the low levels of oxygen achieved and the corresponding boiler efficiencies
for all the tests conducted.

Boiler Efficiencies

Boiler efficiencies were computed based on data using both output/
input and heat loss methods. Enough time was allowed during each data-
taking period to be able to obtain meaningful averages. The data sheets,
including reduced results and summaries, are presented in Appendix B.
All the efficiencies computed are for minimum oxygen (or excess air)
conditions obtained after fuel valve and exhaust damper adjustments were
made and stable readings were achieved. Therefore, they may be regarded
as the maximum achievable efficiencies subject to the environmental
constraints on smoke and CO levels. These results are plotted against
both boiler steam output and water concentration in the fuel (or emulsion)
as shown in Figures 16 and 17. The results presented in Figures 15, 16,
and 17 show that:

---

*Believed to be due to a different tank of oil (tank no. 2) being used.

1. The efficiencies obtained by the heat loss method exhibit less scatter than those by the output/input method.

2. The efficiencies tend to decrease with the increase of both boiler steam output and water concentration in the fuel.

3. Emulsion burning appears to result in lower, instead of improved, boiler efficiency.

Figure 18 is a summary plot of the net stack gas temperature versus boiler load for all the test conditions. It shows that this temperature is reasonably low and increases with the boiler load, as is generally the case. This result is attributable to the clean fire side boiler heat transfer surfaces and efficient boiler operating conditions.

To compute dry stack gas loss (Equation 10), both O_2 and CO_2 measurements are required, but during the tests, the CO_2 analyzer did not perform consistently. Since there is a fixed relationship (Equation 3) between CO_2 and O_2 for a given fuel, calculated values were substituted for all the CO_2 measurements. Thus, the efficiency by the heat loss method becomes dependent on O_2 measurements alone, and the results would necessarily be subject to less random scatter. The efficiency obtained by the output/input method, on the other hand, is based totally on independent measurements of flows and is therefore subject to more experimental errors. As a result, more scatter was expected for the efficiencies computed by the output/input method than by the heat loss method.

The test procedure required that the boiler be adjusted to its most efficient operating condition before data taking began. Therefore, the margin for the emulsion to further improve the boiler efficiency was very narrow. At this point, it should be noted that the results of microexplosions, due to the water particles in an emulsion, are the basis for the claim that complete combustion is promoted with minimal combustion air. Therefore, since the boiler was operated at very low oxygen (~1%), which corresponds to ~5% excess air, and since the indicator

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for incomplete combustion CO was consistently at low levels (<90 ppm), it is rather doubtful that additional benefits, if any, might result from microexplosions. Furthermore, water in fuel extracts a finite amount of energy from the fuel (~1% for 14% water in fuel). These explanations may partially answer why somewhat lower boiler efficiencies result when burning emulsions.

Boiler Operations

Water in no. 6 fuel oil emulsions could be fired in the same manner as no. 6 oil without difficulties. Other than the installation of the emulsification unit, no modifications to the boiler were necessary. Since the emulsions were switched on only after the boiler attained steady operating conditions with no. 6 oil, it is not known whether they could be successfully fired to start up a cold boiler.

When the burner fuel is first switched from no. 6 oil to emulsions, the immediate and apparent change is a cleaner, shorter, bushier, brighter flame. These flame characteristics readily lead one to believe that a better and more efficient combustion condition has been achieved. Since the air admitted to the burner under this situation remains unchanged while a portion of the oil is displaced by the water, this observation is but the result of a "leaner" combustion condition. To maintain the same steam output, more fuel (oil plus water) must be admitted to the burner. Once the fuel valve is opened up to compensate for this oil deficiency to meet the steam demand, the flame changes back to its original appearance.

CONCLUSIONS

This test program was carefully planned and executed to determine the measurable benefits of burning water-oil emulsions as fuels in a Navy boiler. Emulsions with water concentrations up to 15% in no. 6 oil can be fired in the same manner as firing straight no. 6 oil. Since

water in the emulsion actually displaces the oil, the volumetric flow of the emulsion must be increased to maintain the steam pressure and to meet the steam demand. Any benefits of burning emulsions are, at best, ambiguous.

ACKNOWLEDGMENT

Mr. R. S. Chapler's competent help in conducting the tests and in data reduction, contributions of Messrs. G. Clark, W. Jackson, and the boiler crew of the Public Works Department, NWC, China Lake, Calif., in making this test work possible are gratefully acknowledged.

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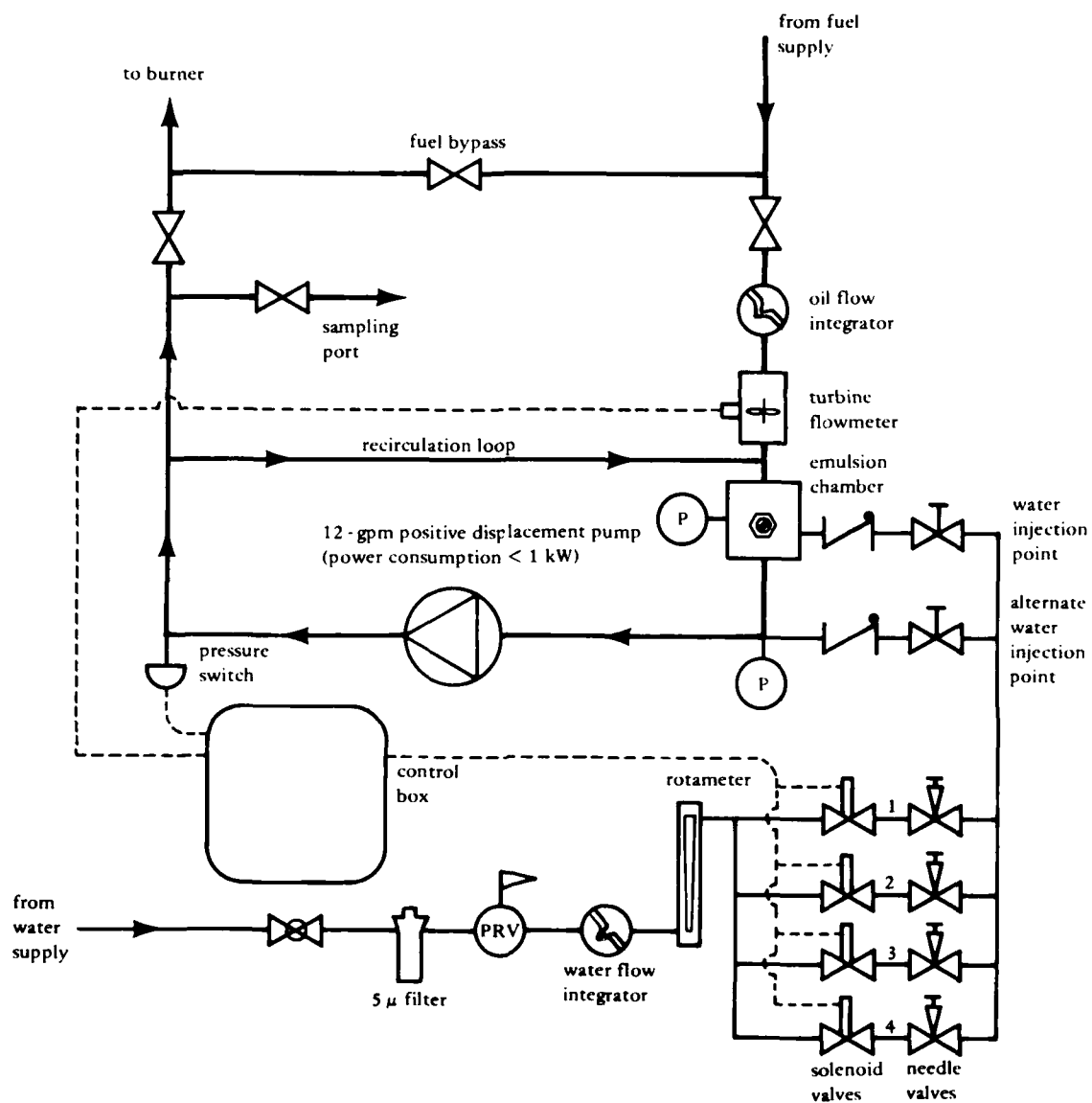
Figure 1. Emulsification system.
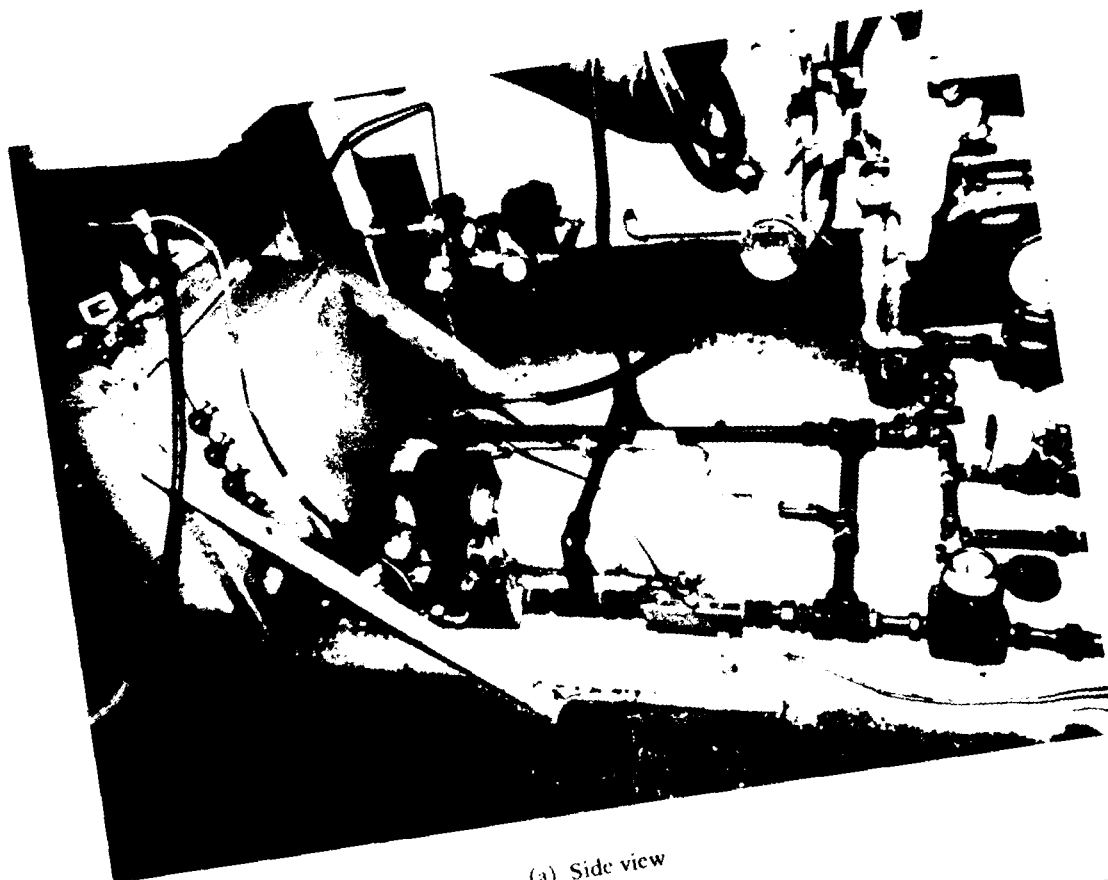
(a) Side view
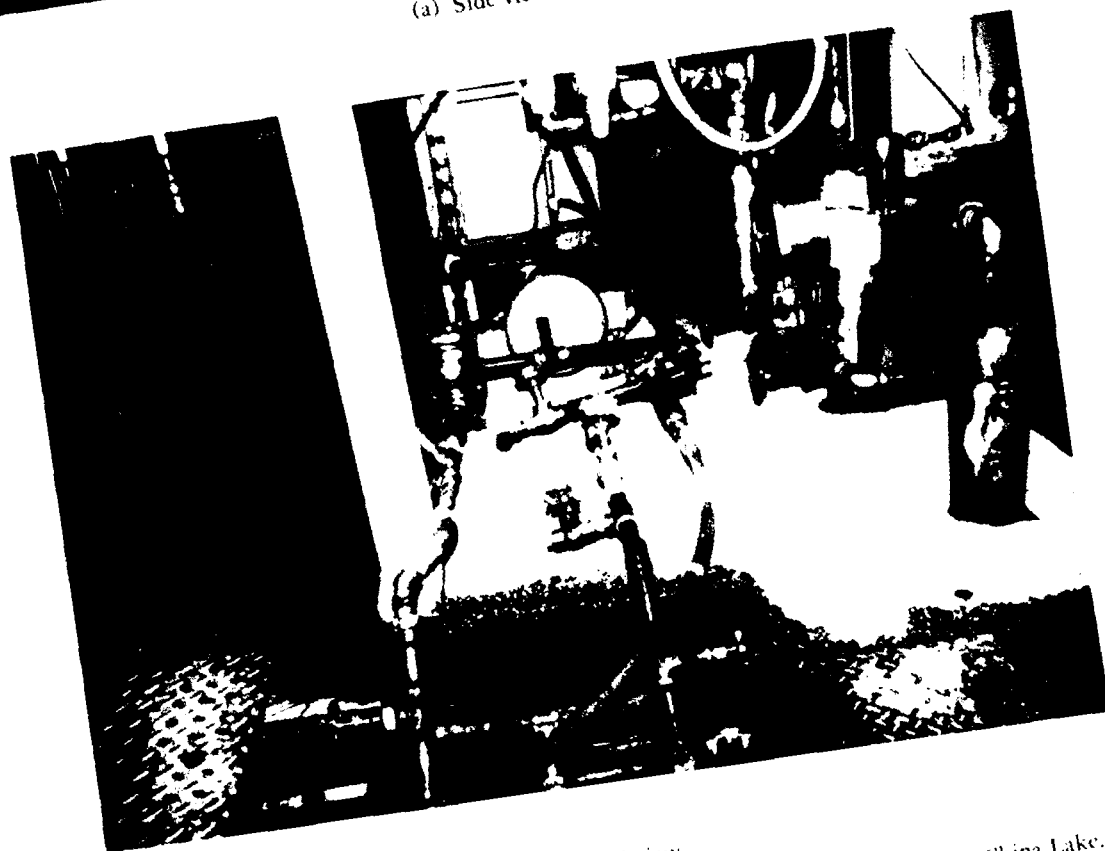
(b) End view

Figure 2. Emulsification system installed on boiler No. 8 at Naval Weapons Center, China Lake.

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(b) Front view of boiler No. 8 for detailed tests

(a) Partial view of boiler No. 4 for preliminary tests

Figure 3. Boilers used for testing water - in - oil emulsions.
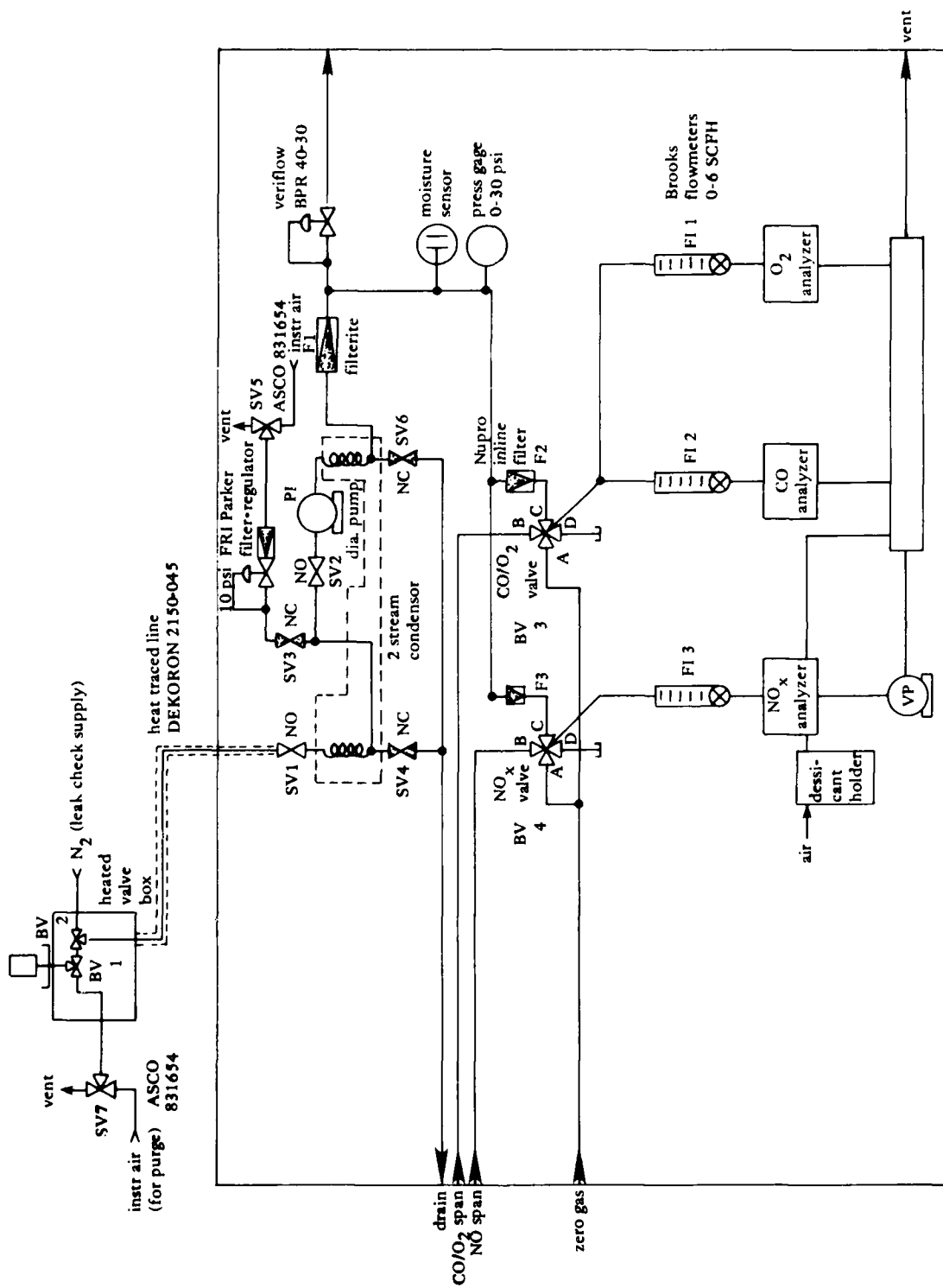
Figure 4. Schematic of automatic stack gas analysis system.
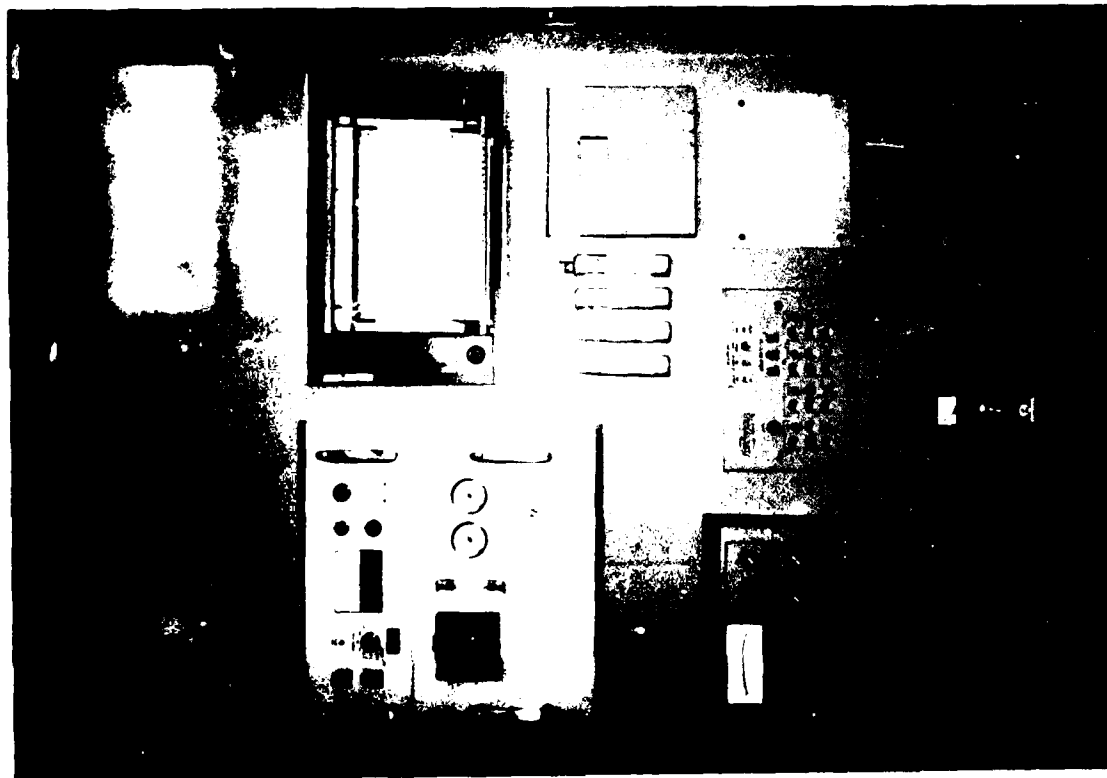
(a) Front view
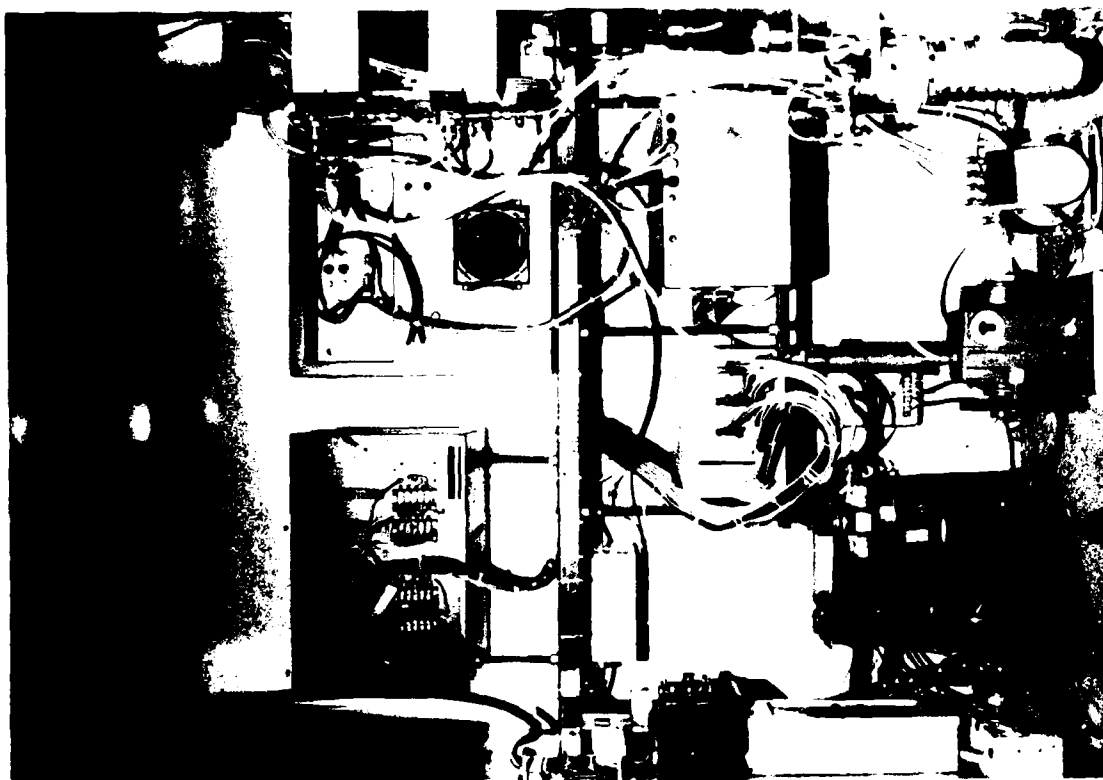
(b) Interior view (from rear)

Figure 5. Automatic stack gas analysis system.

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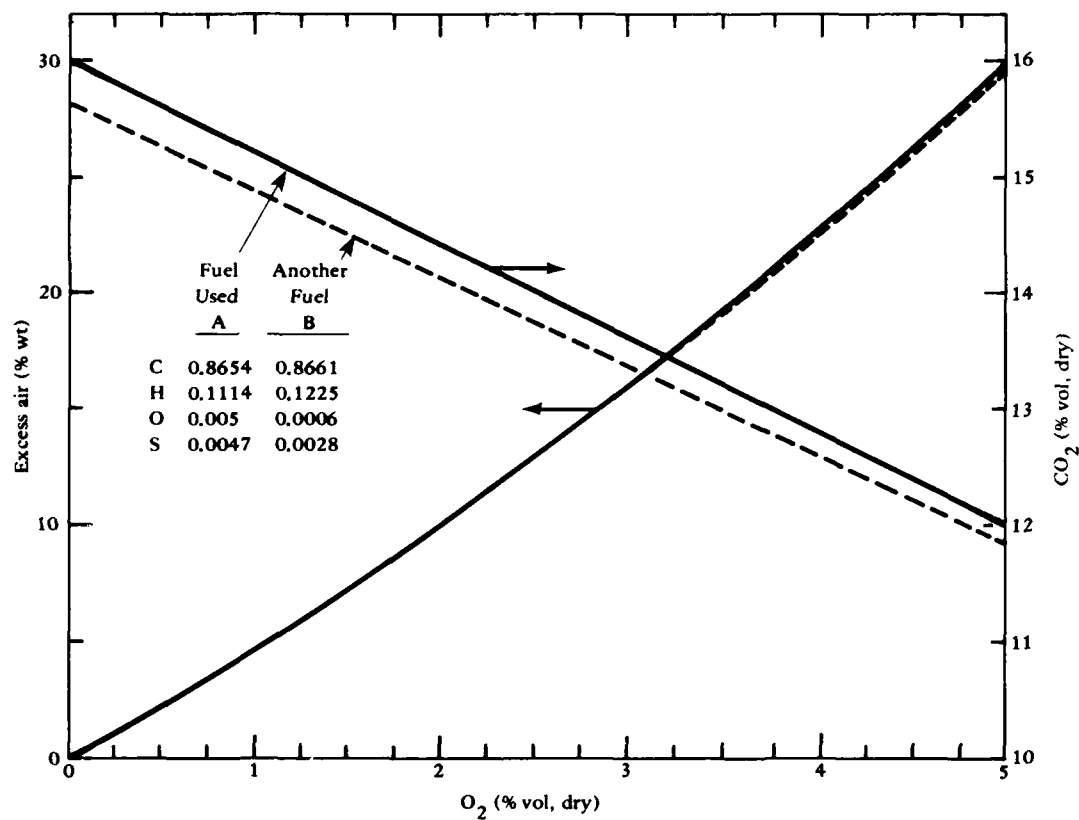
Figure 6. Effects of fuel composition on the relationship between O_2 and CO_2 or excess air.
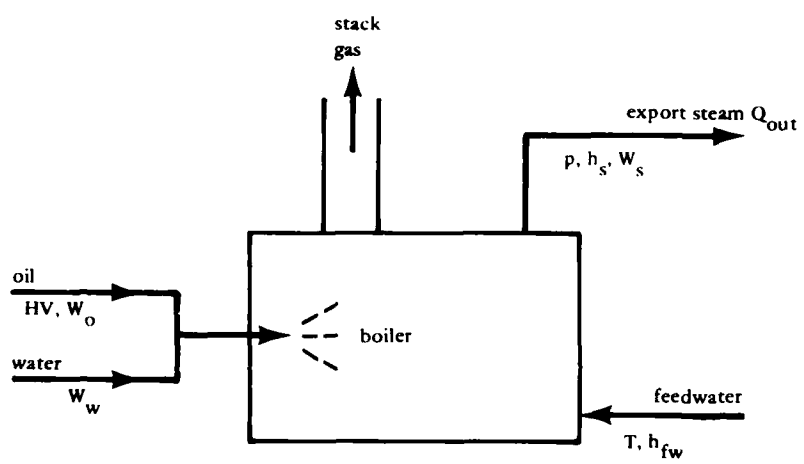
Figure 7. Notations used in boiler efficiency calculations.

Chart Speed (9 min per division)
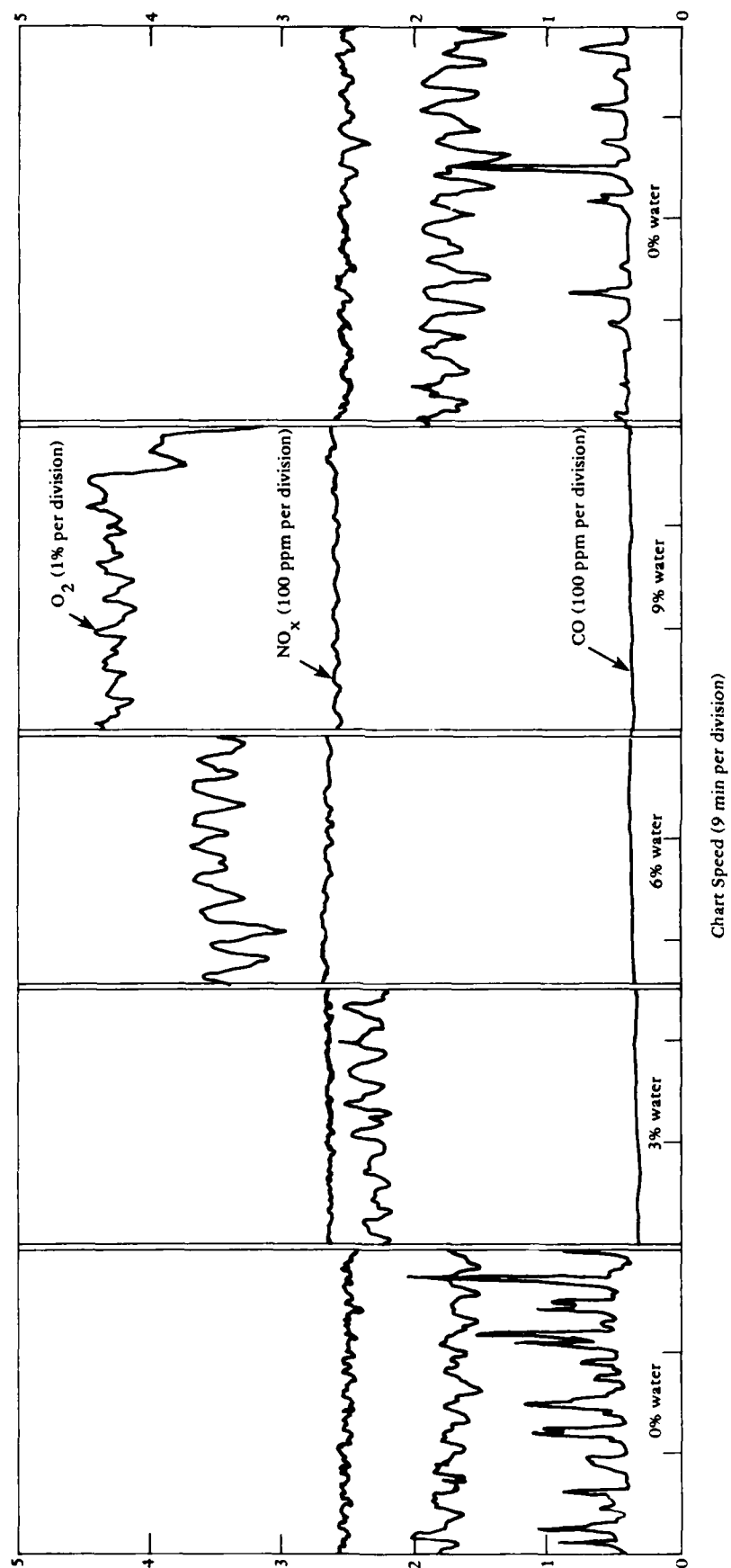
Figure 8. Effects of water concentration in emulsion on O_2, NO_x, and CO at fixed fuel flow rate and air supply.

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(b) Flue damper control linkages

(a) Fuel control valve cam

Figure 9. Boiler components for adjustments.
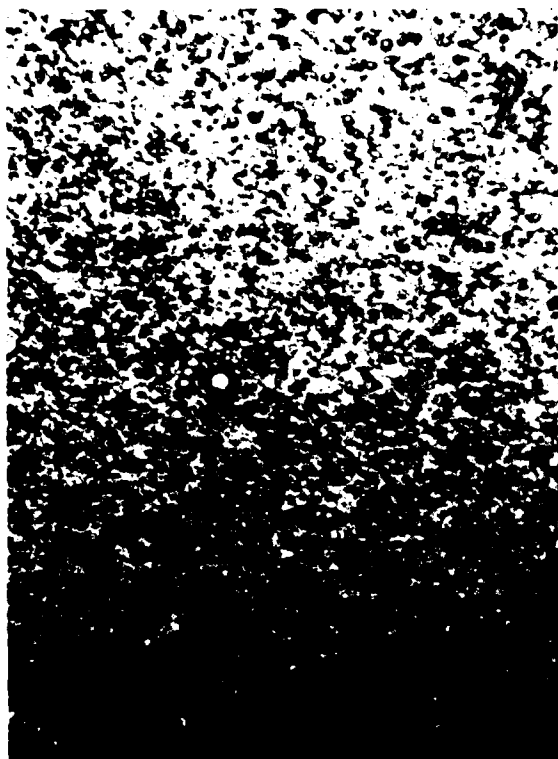
Figure 10. Microscopic features of water-in-no. 6 oil emulsions at indicated water concentrations (Kodak slide film ET135, 160 tungsten, 1 sec exposure, 40 magnification).

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Boiler Load
Range (klb/hr):

▽ 5.4 - 6.4

△ 6.5 - 7.4

○ 7.5 - 9.7 - Tank 2 fuel used

upper operating limit

Bacharach Smoke Spot Number

severe sooting
heavy sooting
moderately heavy sooting
moderate sooting
slight sooting
no sooting expected

Water in Fuel (% wt)
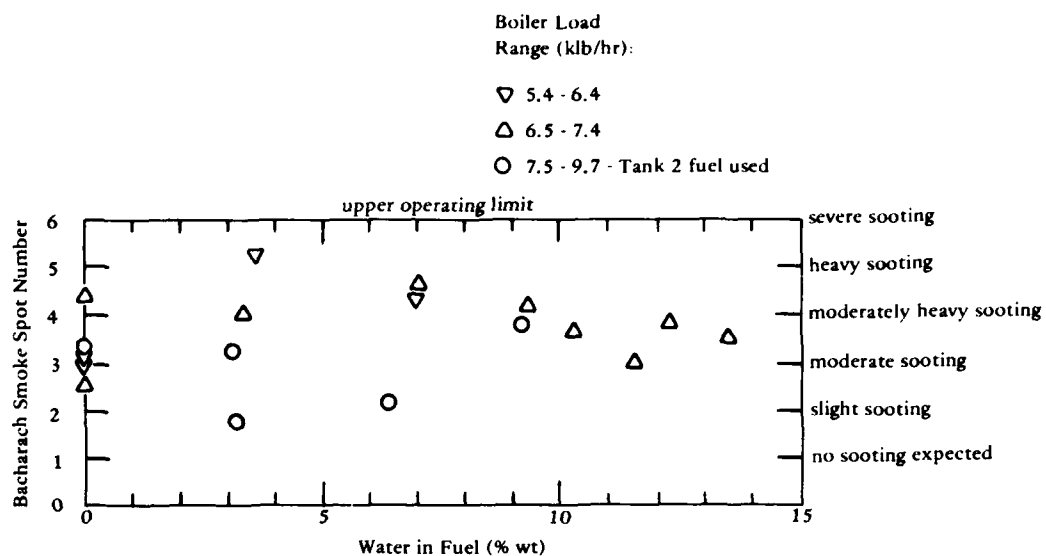
Figure 11. Effect of water on smoke emissions.

upper operating limit

CO, at 3% O_2 (ppm)

Boiler Load
Range (klb/hr):

▽ 5.4 - 6.4

△ 6.5 - 7.4

○ 7.5 - 9.7 - Tank 2 fuel used

Water in Fuel (% wt)
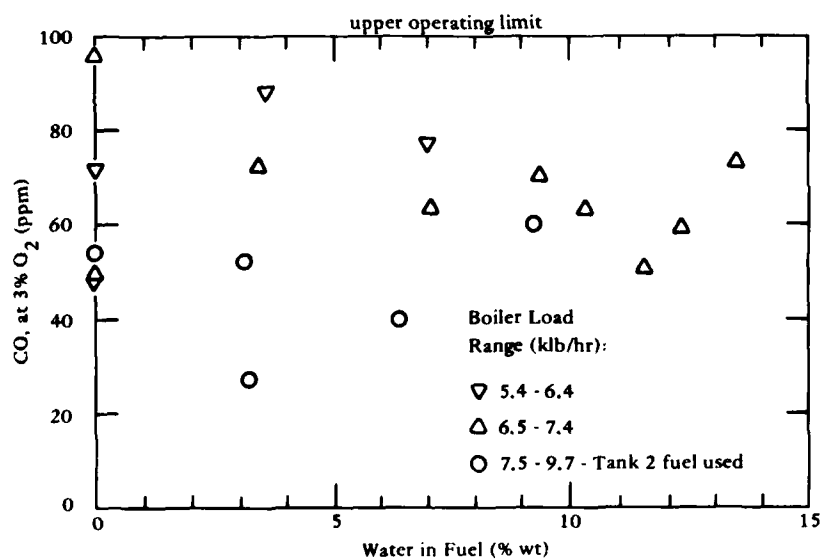
Figure 12. Effect of water on carbon monoxide emissions.

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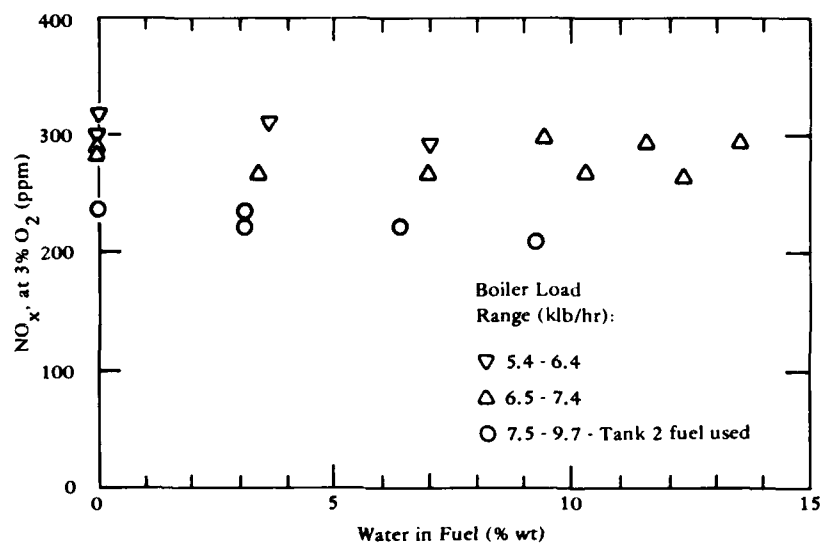
Figure 13. Effect of water on nitrogen oxide emissions.
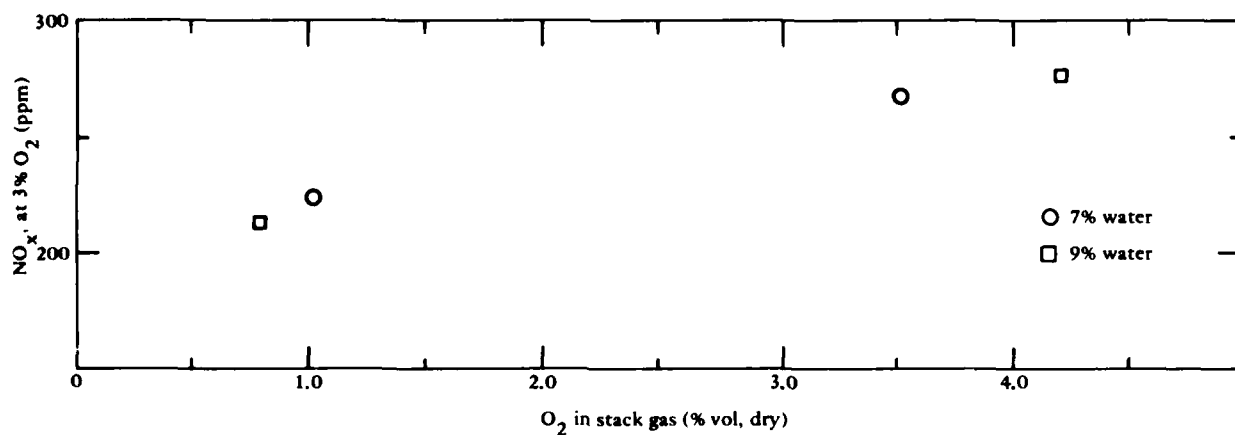
Figure 14. Achievable oxygen (or, excess air) reduction through adjustments.

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Efficiency by Heat Loss Method (%)

85

84

83

82

81

80

0   1.0   2.0

O_2 (% vol)

Water Concentration
(% wt)

▽   0
△   3
○   7
□   9
◇   12
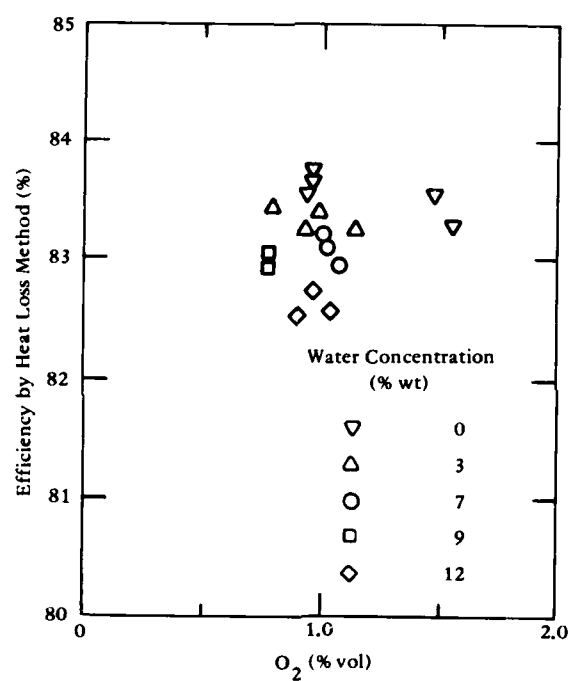
Figure 15. Performance of emulsion burning as a boiler fuel -
boiler efficiency versus O_2 concentration.
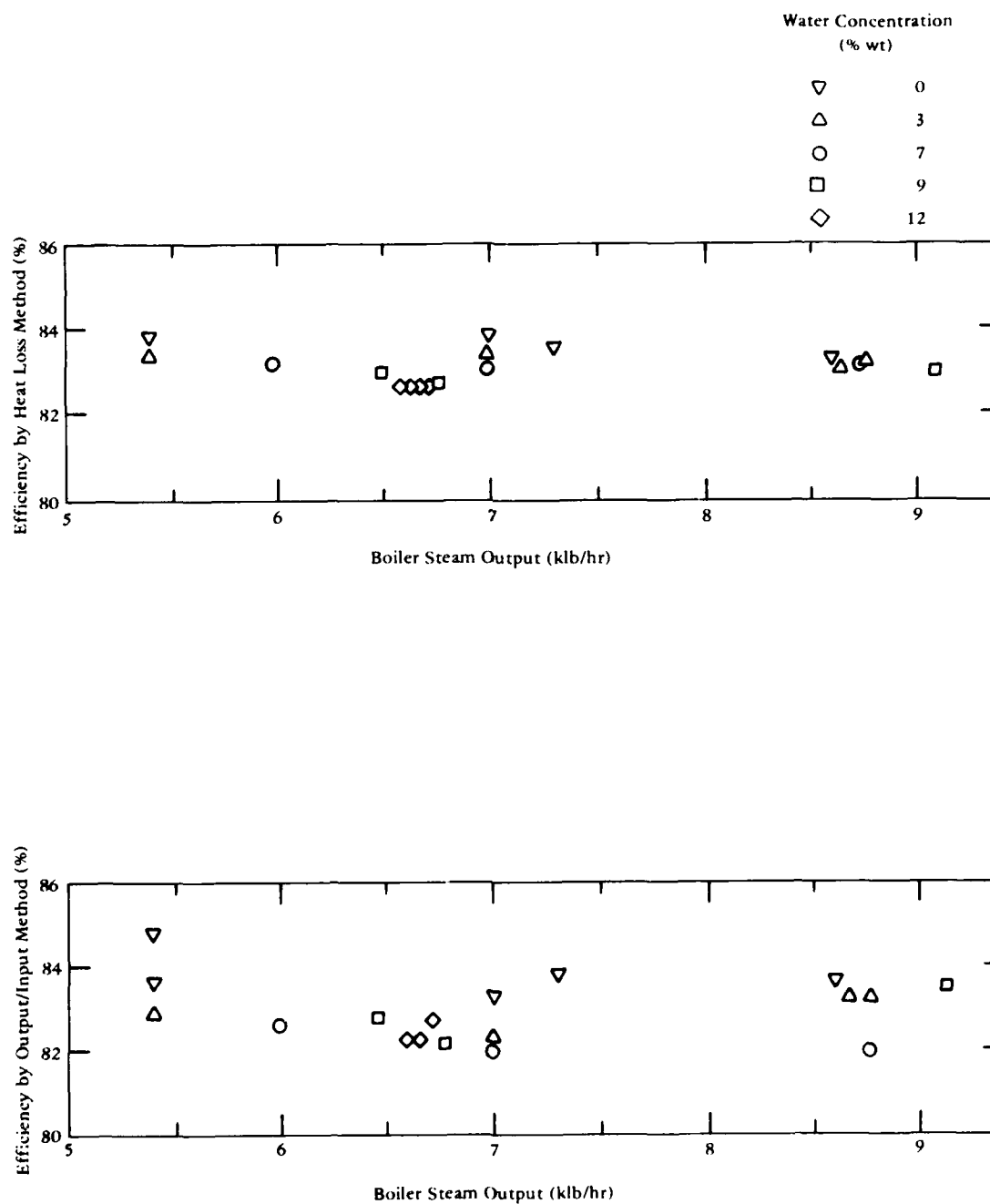
Figure 16. Performance of emulsion burning as a boiler fuel -
boiler efficiency versus steam output.
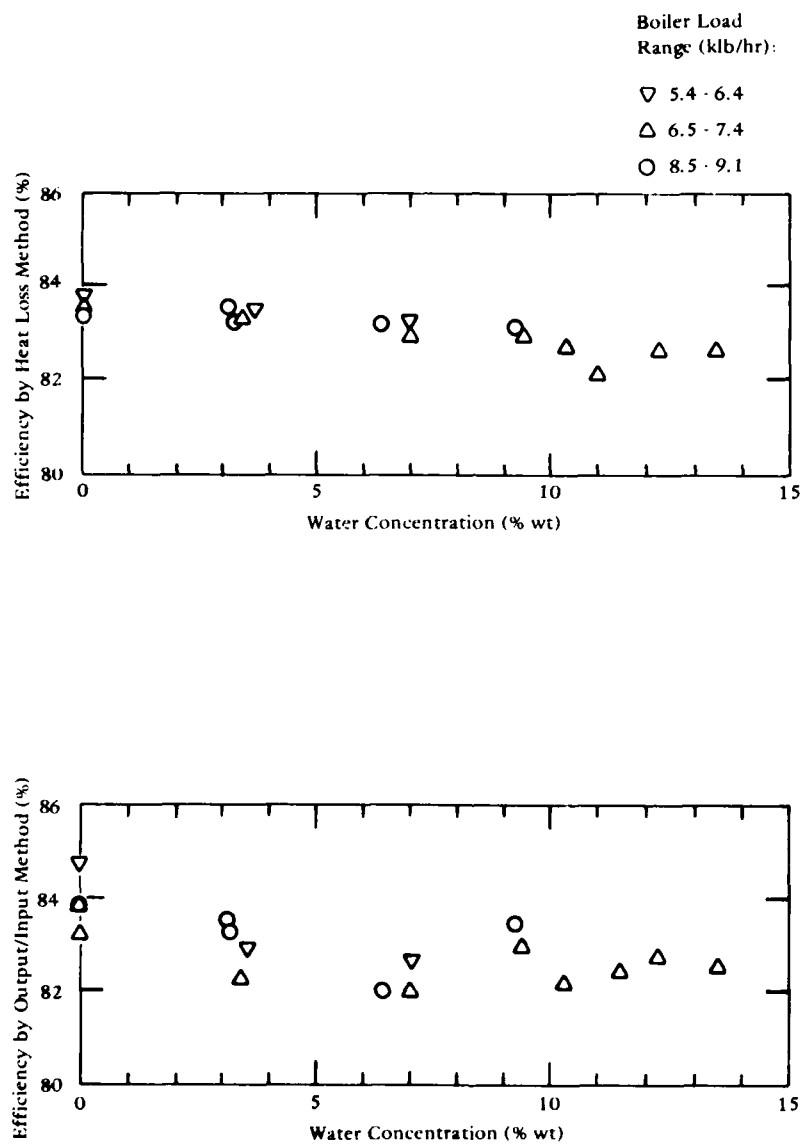
Figure 17. Performance of emulsion burning as a boiler fuel -
boiler efficiency versus water concentration.
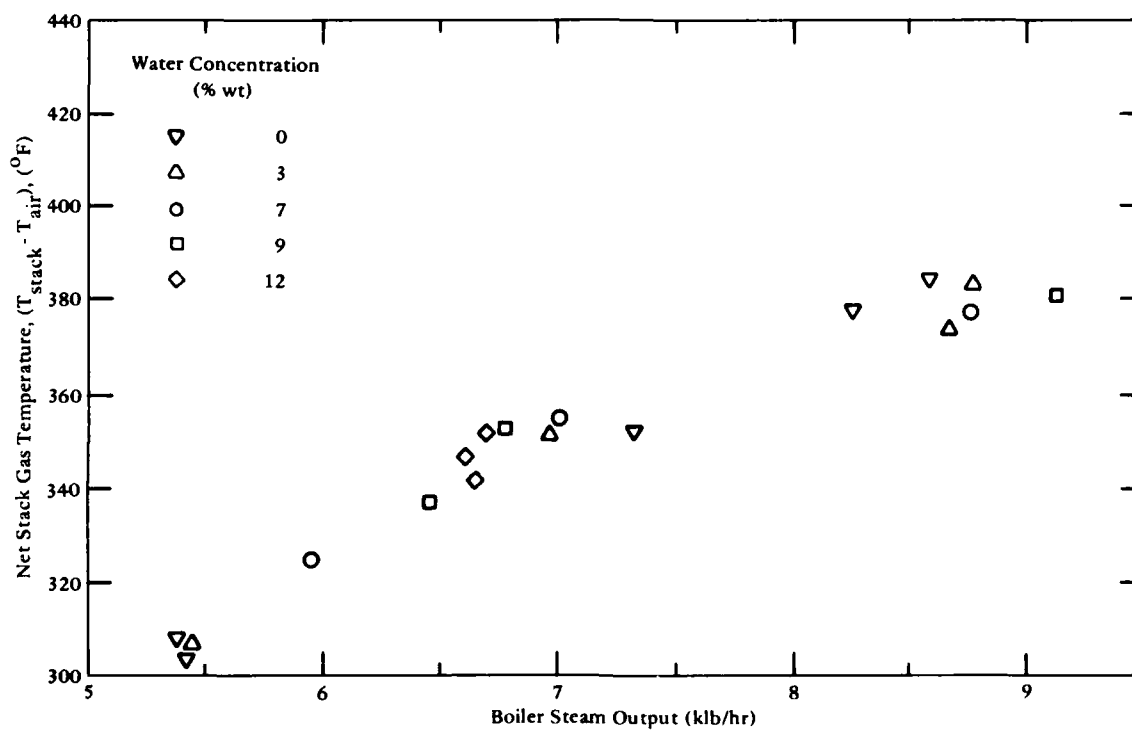
Figure 18. Stack gas net temperatures at all test boiler loads.

Appendix A

EFFECTS OF SWITCHING FROM OIL TO EMULSION

The oil flow control valve of a burner is a volumetric device. At a given volumetric flow of oil and the air intake settings (normally coupled to the oil flow), switching from oil to water-in-oil emulsion means a decrease of the oil flow by the amount of water in it. As a result, the air supplied to the combustion system becomes excessive. Excess air is a primary measure of energy loss through the stack. Thus, switching from oil to emulsion without properly adjusting the flow controls to compensate for this effect will cause the boiler to run inefficiently.

Following the discussions given in the text on combustion calculations, let

$$A = \frac{8}{3} C + 8H - 0 + S = \text{stoichiometric oxygen requirement, lb oxygen/lb fuel}$$

X = excess air, % weight of stoichiometric air

W = weight

c = concentration of water in emulsion, % weight

and subscripts

    a = air
    f = fuel
    o = oil
    w = water
    A = fuel A
    B = fuel B

For fuel A, the weight of air for combustion may be expressed by the amount of oil W_{oA} in it and the amount of excess air X_A used, as follows:

$$W_{aA} = \frac{1 + X_A}{0.2315} A_A W_{oA}$$

From the water concentration of fuel A

$$c_A = \frac{W_{wA}}{W_{fA}} = \frac{W_{wA}}{W_{wA} + W_{oA}}$$

Or

$$W_{oA} = \frac{1 - c_A}{c_A} W_{wA} = (1 - c_A) W_{fA}$$

Thus,

$$W_{aA} = \frac{1 + X_A}{0.2315} A_A (1 - c_A) W_{fA} \qquad \text{(A-1)}$$

Similarly,

$$W_{aB} = \frac{1 + X_B}{0.2315} A_B (1 - c_B) W_{fB} \qquad \text{(A-2)}$$

Since the same oil is used for the emulsions (fuels A and B)

$$A_A = A_B \qquad \text{(A-3)}$$

and the only difference between fuels A and B is the amount of water in them, or the water concentrations c_A and c_B. For the same fuel valve opening, assuming the difference in density between fuels A and B is small,

A-2

$$W_{fA} \approx W_{fB} \tag{A-4}$$

With no change in air intake (air control being coupled to oil flow),

$$W_{aA} \approx W_{aB} \tag{A-5}$$

Combining Equations A-1 through A-5,

$$(1 + X_A)(1 - c_A) = (1 + X_B)(1 - c_B)$$

or,

$$X_B = \frac{1 - c_A}{1 - c_B}(1 + X_A) - 1 \tag{A-6}$$

Equation A-6 gives the resulting excess air when fuel A is switched to fuel B without any burner adjustment. It shows that the excess air is increased when $c_B > c_A$ and vice versa.

Consider the following two cases:

(1) $c_A = 0$. This means that fuel A is oil. Equation A-6 becomes

$$X_B = \frac{1 + X_A}{1 - c_B} - 1$$

Clearly, switching from oil to emulsion will result in higher excess air and a bright, clean flame, but a lower boiler efficiency.

(2) $c_B = 0$. This means that fuel B is oil. Equation A-6 becomes

$$X_B = (1 - c_A)(1 + X_A) - 1$$

This indicates that switching from emulsion to oil will result in a decrease in excess air and perhaps smoky flame.

A-3

Date/Time	Fuel Flow / Oil Temp (F.O.#6)	Steam Flow (Klb)	Pressure	Feedwater Temp	Water Flow / Temp / Back Temp	Air Temp	O₂/CO₂	CO/NOx	Smoke	Emission %	Efficiency (heat input method)	Efficiency (heat output method)	Excess O₂ CO₂ CO NOx	Corrected CO NOx	Efficiency based on O₂ (radius/MBtu)	Load
3/18/82																
17:4	194.50/187	852 25/60	99.9	206	0 / 76 / 77	459 3.3	16 43	235 —								
17:29	222.25/189	855 5/60	98.8	205	78 / 77	453 3.38	15.9 45	240 2				15.95 43	235			
17:34	208.50/199	859 9/60	100	206	77 / 77	453 3.4	16 43	238 2					238			
17:39	214.25/198	862 14/60	99.9	204	78 / 77	453 3.5	15.9 43	240 2								
17:44	220.40/198	866 2/60	99.8	206	77 / 77	454 3.8	15.4 43	235 2								
17:49	224.40/188	869 3/60	99.7	206	77 / 75	455 3.6	16.0 43	236 2								
17:54	223.25/189	872 5/60	99.9	204	78 / 76	457 3.55	15.9 43	235 2								
18:04	244.50/190	879 33/60	99.5	206	79 / 77	456 4.0	15.7 44	225 4								
19:14	256.85/189	886 4/60	99.8	205	78 / 76	455 3.7	15.9 45	230 3								
18:25	270.2/189	893 24/60	99.9	208	77 / 74	458 3.7	16.0 43	240 2								
avg	73.70/198.1 / 41 4/60 50.11667	4.95010	99.9	208	775 76.5	455 3.64	15.89 43.4	236 2.64		0	81.60		3.51 — 42 243	43 250	13.29	82.52 8.252
3/18/82 (F.O.#6)																
20:15	644.00/194	958 23/60	100.2	206	0 / 81 / 77	461 4.69	15.2 65	255 3								
20:15	658.45/195	966 14/60	100.4	207	81 / 77	460 4.35	15.5 60	257 4								
20:25	668.70/195	973 31/60	100.1	207	82 / 77	459 4.65	15.3 55	250 4								
20:45	680.80/195	980 14/60	100.4	206	82 / 77	460 4.55	15.3 60	250 3								
20:55	693.00/195		100.4	206	81 / 79	461 4.46	15.5 50	240 3								
21:05	705.45/194		100.2	206	81 / 74	461 4.96	15.3 58	253 4								
21:15	711.80/194	861 3/60	100.2	205	80 / 73	460 4.10	15.3 52	253 2								
21:25	720.00/194	868 2/60	100.2	207	81 / 72	461 4.30	15.6 58	250 3								
avg	24.15 195.1 / 13 3/60 13.58333	50.11667	100.3	206	81.3 75.8	461.7 4.67	15.38 61	251 2.25		0	83.67		1.65 — 58 255	54 239	14.71	83.26 8.391
3/18/82 (EM-9)																
23:00	688.00/196	958 28/60	99.6	208	3.07 / 84 / 75	489 4.35	13.5 48	255 1								
23:10	300.05/195	966 14/60	99.5	207	4.29 / 84 / 75	489 4.15	13.6 48	260 1.5								
23:20	313.22/194	973 31/60	99.5	207	5.54 / 85 / 85	488 4.20	13.6 50	255 1.5								
23:30	326.25/194	980 14/60	99.5	207	6.755 / 85 / 85	489 3.90	13.7 50	255 2								
avg	38 0.5/ 195.5 / 21 5/60	14.91667		207.3	3.685 84.5 80	489 4.15 136.0	13.60 256	256 1.25	8.382		80.42	4.20 — 35 260	38 280	12.76	81.93 8.7333
	22.30 1947	21.83333		207	2.445 84.7 81.7	489.7 4.06 13.67 493	13.67 493	256.7 1.3								
3/18/82 (EM-6)																
00:01	995.05/195	986 2/60	99.8	205	7.310 / 84 / 88	487 3.30	14.2 54	260 3								
00:11	946.45/195	992 18/60	99.8	207	8.160 / 85 / 87	483 3.65	13.8 50	260 1								
00:21	959.20/195	999 35/60	99.8	207	9.000 / 84 / 87	480 3.10	14.1 52	260 1								
avg	24.15 195.1 / 13 3/60	13.58333	99.8	205.7	7.680 85 87.3	483.3 3.35 14.03 52	14.03 52	260 1.67	7.091		81.57	3.49 — 36 266	37 270	13.70	81.55 8.××
3/18/82 (EM-3)																
00:29	971.75/195	006 52/60	100	207	9.530 / 85 / 89	476 2.65	14.9 44	220 2								
00:39	984.32/196	014 1/60	100.2	207	9.989 / 85 / 90	473 2.36	15.0 40	260 1.5								
00:49	997.20/196	021 37/60	100.2	207	10.382 / 86 / 90	470 2.35	13.2 40	255 2								
avg	25.75 1957 / 14 37/60 14.61667		100.13	207	0.792 85.6 89.7	473 2.42 14.97 41.3	14.97 413	258 1.83	3.166		83.15	1.14 — 30 262	27 221	15.16	83.25 8.××
3/19/82 (EM-3)																
00:55	032.55/197	041 57/60	100.4	206	10.510 / 85 / 89	461 1.60	15.0 80	245 4								
00:05	043.92/196	049 9/60	100.2	205	10.894 / 84 / 89	462 1.70	15.5 80	240 4								
00:15	057.00/196	056 3/60	100.2	206	11.212 / 85 / 90	463 1.10	15.2 50	240 2								
avg	25.15 1963 / 14 34/60 14.43333		100.3	205.7	0.772 85.7 89.7	462.7 1.70 15.23 70	15.23 70	241.7 3.33	3.119		82.23	0.85 — 58 248	52 221	15.33	83.54 8.××
3/18/82 (EM-6)																
00:15	113.70/196	088 21/60	99.8	208	15.770 / 85 / 90	465 1.85	15.1 52	255 3								
00:15	126.70/196	095 5/60	100	207	16.586 / 84 / 90	467 1.95	15.1 75	250 2								
00:35	139.45/196	103 4/60	100.2	207	17.335 / 84 / 88	467 2.20	14.9 45	252 1.5								
avg	25.15 196 / 14 35/60 14.58333		99.87	207.3	1.625 84.3 89.3	466.3 2.00 15.03 567	15.03 567	252.3 2.17	6.429		81.96	1.62 — 45 249	4 224	15.20	83.16 8.××

B-2

Table of combustion/boiler test data (handwritten log sheet). Columns (left to right): Time, Fuel Oil Temp, 20 Oil Temp, Transfer Rdg, Pressure, Feedwater Temp, Water Feed Rdg/Temp, Air Inlet Temp, Stack Temp, O_2/CO_2, CO/NOx, Smoke, and additional analysis columns (CO_2, etc.).

Time	Fuel Oil Temp	20 Oil Temp	Transfer Rdg	Pressure	Feedwater Temp	Water Feed Rdg/Temp	Air Inlet Temp	Stack Temp	O_2/CO_2	CO/NOx	Smoke
3/31/82	**(FO6)**										
11:35	181.20	190 223	4%0	99	197	0	77	421 0.68	15.0 205	277	3
01:40	196.20	190 232	2%0	99	198		74	422 0.90	14.7 58	294	5
01:55	211.50	191 241	1%0	99	198		79	422 1.18	14.5 60	292	5
12:10	22.75	190 247	4%0	98.5	198		80	424 0.90	14.2 58	302	5
02:35	242.24	191 258	9%0	98.5	198		77	426 1.15	14.5 115	273	4
1:00	81.28	190.4		98.2	197.8		77.6	423 0.96	14.66 99.2	288 4.4	
3/31/82	**(FO6)**										
12:00	82.70	196 591	26%0	98.6	211	0	86	388 1.02	14.7 42	310	4
12:20	83.20	189 600	3%0	98	209		83	387 0.78	14.4 40	315	4
12:40	843.00	187 608	7%0	98.2	211		80	387 0.80	14.4 90	330	3
13:00	858.40	196 618	4%0	99	211		77	387 0.73	14.1 32	335	2
13:20	873.50	191 628	9%0	98.6	204		77	380 1.0	13.6 24	340	2
1:21	80.84	193.3	37 36%0	98.5	209.8		81.3	385.8 0.97	14.28 48.4	326 3.0	
1:21	81.28	198	37.1/1467	98.35	210.5		83?	395 0.83	14.45 92	3225 3.3	
3/31/82	**EM-3**										
13:57	900.20	180 643	14%0	98.6	199	14.460	81 76	381 0.86	14.1 69	312	4
14:12	910.10	180 649	40%0	98.8	196	12.035	81 75	380 0.90	14.0 150	308	4
14:28	925.20	179 656	58%0	99.4	193	12.295	81 74	382 0.81	14.4 110	300	4
14:43	936.70	178 663	13%0	99.0	190	12.910	81 73	380 0.41	14.7 108	298	6
14:58	948.60	182 670	5%0	98.2	189	13.330	82 78	385 0.65	14.7 700	262	7
1:01	74.6	179.8	28 4%0	98.6	199.4	4.470	84.2 75.2	382.0.73	14.36 227.4	340 5.2	
1:59	81.28	198	27.13	97.43	192.75	2.730	81 75	393 0.69	14.45 267	294.6 5.5	
3/31/82	**EM-6**										
15:45	988.50	182 692	15%0	97.8	189	16.790	82 70	397 1.22	14.0 143	312	3
16:00	003.00	182 699	37%0	97.8	193	17.200	83 73	398 1.15	14.6 40	300	4
16:15	016.40	185 707	7%0	97.8	196	18.146	84 72	398 1.10	14.4 38	310	4
16:30	02940	184 714	2%0	97.9	194.5	19.080	83 74	399 0.84	14.8 120	277	5.5
16:45	042.40	193 722	9%0	97.8	186	19.930	83 76	389 0.27	14.8 90	290	5
1:00	53.90	182.2	29 6%0	97.8	192.1	3.740	83.2 73.0	398.1 1.01	14.60 842	295 4.3	
1:45	59.6	183.7	33 3%0	97.43	193	2.730	83.5 73.75	395.5 .97	14.9 62	21.3 2.6	
3/31/82	**EM-9**										
17:48	104.20	184 754	5%0	98	190	25.570	80.75	411 0.95	14.6 58	295	3
18:03	118.60	184 762	4%0	98	191	26.860	80.7%	413 0.80	14.9 60	308	3
18:21	135.50	184 772	5%0	98.2	191	28.445	80 74	414 1.00	14.8 42	278	5
18:36	150.70	183 780	2%0	98.2	192	29.870	81 78	414 0.47	15.0 200	275	5
18:51	163.70	184 788	4%0	98	192	31.190	81 73	414 0.84	14.9 62	270	4
1:00	53.50	183.5		98	191.2	5.620	80.5 75.5	413.0 0.80	14.44 88.6	288.6 7.2	
3/31/82	**EM-15**										
19:28	200.80	185 859	4%0	98	194	35.310	84 69	418 1.05	14.5 46	293	3
19:43	215.30	184 817	23%0	98	194	36.970	83 74	418 1.05	14.8 38	300	1.5
19:58	223.90	184 870	34%0	97	196	38.740	82 77	419 0.60	14.8 50	290	3.5
20:13	244.30	185 833	5%0	98	195	40.450	82 71	419 1.02	14.8 40	295	3
20:28	258.90	184 842	6%0	98	195	42.170	82 71	419 1.03	14.8 41	295	4
1:00	58.10	184	33 3%0	98	194.6	6.860	82.6 71.6	411.88	14.10 13	294 3.0	
3/31/82	**EM-15**										
21:00	290.75	185 859	4%0	98	194	46.820	83 70	420 1.00	14.5 45	300	5
21:10	300.75	185 865	14%0	98	196	47.890	81 76	420 0.75	14.7 70	280	4
21:20	310.10	184 870	1%0	97	196	49.240	82 77	419 1.20	14.9 47	285	3
21:30	320.10	184 876	27%0	97	195	50.630	86 80	419 1.23	14.0 34	308	3
1:30	29.35	184.5	16 8%0	98	195.6	7.745	83 77.8	419 1.045	14.55 49	393.7 3.5	

(Right-side analysis columns, partially legible, include readings such as: O_2, CO, N_2, CO, H_2 CO_2, and summary values: 83.75, 83.34, 7.03; 83.48, 84.79, 5.92; 83.42, 82.86, 83.1; 83.14, 80.15, 5.05; 82.95, 82.28, 6.46; 82.73, 82.55, 6.64)

B-4

Date Time	FuelFlow/Wt Rdg (g/hr Temp)(E-M6)	SteamFlow Rdg	Pressure	Feedwater Temp	Waterflow Rdg	Air Temp	Stack Temp	O2/CO2	CO/NOx	Smoke	O2	CVs	CO	NOx	CO	NOx	Smoke
4/1/92																	
11:41	201.05 187 403 26%		100.2	211	53.335	75 78	449 1.62	14.9 37	280 6								
11:59	232.70 186 415 1⅞		101	209	55.325	74 78	446 1.30	14.8 35	323 1								
12:10	247.51 186 424 3⅞		101	208	56.4%	74 79	440 1.70	14.8 32	328.8 2.5								
12:30	263.20 185 434 3⅞		101	209	57.750	74 80	440 1.60	14.8 37	932 2								
12:45	277.75 186 443 4⅞		101	202	58.935	74 75	438 1.30	14.8 33	303 1								
13:00	291.35 185 452 4⅞		101.2	199	60.065	74 77	428 1.70	14.8 37	322 2				1.48 14.93 53 348 49		284 14.84	82.70 7.55
1:04	52.25 155.8 37 2⅞		101.04	205.4	4.756	74 77.8	445 1.72	14.80 342	321.6 1.7	5.107	80.47						
45	45.25 155.4 37.36 6⅞		101	207.5	4.130	74 78	411 1.72	14.70 343	321.5 1.6								
4/1/82				204.5	3.575	74 78	435 1.77	14.86 35	311.3 1.98								
14:06	355.00 187 499 2⅞		101.5	190	68.375	76 83	430 1.64	15.1 46	317 2								
14:21	371.25 186.5 499 5⅞		101	189	66.0%	77 83	429 1.24	15.1 42	320 4								
14:36	385.50 187 508 4⅞		101	187	67.148	76 83	430 0.88	15.2 80	304 2.5								
14:53	401.90 187 518 3⅞		101	186	68.395	77 84	430 1.39	15.0 43	309 5.5								
15:06	414.30 187 526 1⅞		101	185	69.324	77 84	430 1.00	15.1 49	310 3								
15:30	437.50 186 540 1⅞		101	184	71.095	77 84.5	430 1.20	15.0 49	312 2				1.16 15.45 54 309 49		250 15.09	83.10 7.01
1:09	64.25 186.7 40 1⅞			186.2	5.059	76.8 83.7	429.8 1.40	15.08 51	372.4 3.2	7.75 6	88.89						
	40.28¢33																

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  Wu), Annapolis MD; PWO Annapolis MD; USNA/Sys Eng Dept, Annapolis, MD
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